Cross-Scale Coupling: Modeling Oceanic Variability from the Pacific Basin Scale to Local Coastal Domains Along the North America West Coast (NAWC)

James C. McWilliams
Department of Atmospheric & Oceanic Sciences and
Institute of Geophysics and Planetary Physics, UCLA
Los Angeles, CA 90095-1565
Phone:(310) 206-2829 fax:(310) 206-5219 email: jcm@atmos.ucla.edu

Xavier J. Capet and Francois Colas
Department of Atmospheric & Oceanic Sciences and
Institute of Geophysics and Planetary Physics, UCLA
Los Angeles, CA 90095-1565
Phone:(310) 206-9381 fax:(310) 206-5219 email: francois@atmos.ucla.edu

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LONG-TERM GOALS

Realistic, skillful numerical simulations of oceanic physical-ecological-biogeochemical processes are urgently needed to address many societal problems (*e.g.*, naval operations, climate change, coastal eutrophication, fisheries). An important requirement, as yet rarely met, is the capability of simulating both the global or basin-scale circulation and the more local flows that respond to the larger scale changes ("down-scaling"), and sometimes feedback on them and influence their evolution ("up-scaling"). We have proposed to investigate the space-time structure and causal mechanisms for this cross-scale coupling as it occurs in the oceanic circulation and water properties along the North American West Coast (NAWC) within the context of large-scale changes throughout the Pacific basin. The cross-scale coupling is manifested over a broad range of time scales, ranging from synoptic and intra-seasonal (with cross-scale communication by barotropic Rossby and coastal waves) through seasonal and interannual (with transient currents, mesoscale eddies, and baroclinic waves) to decadal or longer (with slowly varying quasi-equilibrium currents over the whole basin). Simulations will be made both for the Pacific as a whole and for the NAWC regional and local coastal (*a.k.a.* littoral) subdomains, using either eddy-excluding or eddy-permitting grid resolutions for the former and fine mesoscale resolutions for the latter.

OBJECTIVES

Historically, our research on regional oceanic dynamics has mostly dealt with the U.S. West Coast (USWC) between the Mexican and Canadian borders. Taking advantage of this experience, we are currently focusing on the impact of the 1997-1998 El Niño on the ocean dynamics (mean currents and mesoscale variability) and thermohaline structure off California and Oregon. This also has the advantage of providing us with a large *in situ* dataset well suited for model validations. In this first stage of the project, our main goal is to get some insight into the ways through which the basin scale equatorial El Niño signal affects the USWC.

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APPROACH

We are seeking an integrated, coast-wide view of the Pacific + NAWC physical variability. Our general approach is to determine the degree of relevance for four hypotheses and potentially refine them; each corresponds to a specific time/space scale window.

1- Intraseasonal Forcing Effects on the NAWC: we will consider how sequences of synoptic and longer intraseasonal atmospheric events (*e.g.*, storms and their associated coastally trapped wave signals, river run-off, and sea breeze) lead to changes in the NAWC mean state through rectification (*i.e.*, time-averaged fluxes). Our hypothesis, to be tested, is that there is no significant upscaling in either space or time (*i.e.*, none of these phenomena—including coastal waves generated by storms—induces important rectification in the quasi-equilibrium circulation).

2- Local Seasonal Forcing Effects on the NAWC: fluctuations of the quasi-equilibrium on the seasonal scale are primarily induced by local wind variability, with remote influences and buoyancy forcing secondary. In the Marchesiello et al., 2003 simulation of mean-seasonal equilibrium CCS, this interpretation seems valid. Our hypothesis is that the mesoscale-eddy modulation in response to the local seasonal forcing occurs for the entire NAWC region.

3- Remote Interannual Downscaling Effects on the NAWC: on interannual time scales, the quasi-equilibrium of the Mexican, U.S., and Canadian coastal sectors is strongly influenced by the coherent poleward propagation of wave-like anomalies in sea level, pycnocline slope, and circulation. These anomalies are generated, or at least pass through, the tropical region in the up-wave direction from the NAWC (*e.g.*, ENSO variations). Response to local forcing and advective dynamics (especially mesoscale) may modulate wave-instigated fluctuations.

4- Decadal Downscaling Effects on the NAWC: on decadal time scales, the North Pacific variability mainly occurs as a basin-wide atmospheric pattern change, most famously identified as the PDO. Its anomalous forcing induces quasi-stationary, basin-wide changes in SST, pycnocline depth and circulation. Therefore we hypothesize the NAWC decadal variability arises as a quasi-equilibrium response to the combined influence of remote and local surface forcing anomalies.

Practically, our approach involves coupling a low resolution (50 and 25km as of yet) Pacific solution of the Regional Ocean Modeling System (ROMS) together with regional configurations (at high horizontal resolution, typically 5km) focused on NAWC. We will then make sensitivity studies, *i.e.*, calculate and analyze several (Pacific/NAWC) twin solutions that differ from each other by their forcing functions or model configurations. This will help us identify and characterize the key mechanisms involved in down-scaling and up-scaling processes.

WORK COMPLETED

Progress made during the past year covers different aspects of the project.

Taking advantage of recent improvements made by our group on the boundary conditions treatment and downscaling techniques in ROMS, we now routinely downscale basin-scale solutions (SODA-POP reanalysis (Carton and Giese, 2007), CCSM-POP (Large and Danabasoglu, 2006) or UCLA ROMS-Pacific). We evaluated the skill of these solutions for the downscaling in our regional configurations. Some sensitivity experiments of the regional solutions to the downscaled signal frequency at the boundaries have been performed. In the context of ENSO events, regional solutions are significantly improved when information at the open boundaries is updated at a time-scale of a few days (rather than monthly). This is due to the fact that ENSO signals have an equatorial origin and a significant part of the equatorial activity is contained in an intra-seasonal frequency range. We have also continued sensitivity tests on different forcings to improve our ROMS Pacific solutions (at resolutions of 50km and 23km).

A large part of our activity during the last year has consisted of careful analysis of our companion interannual solutions (large domains including the equatorial region at horizontal resolution ≈ 8km obtained for the NAWC and the South American West Coast (SAWC) over the period 1992-2000) (Colas et al., 2007, Capet et al., 2007a).

A downscaling study has also been undertaken in a regional configuration of the Gulf of Alaska (including 3 different levels of embedded grids at 10 km, 3.3 km and 1.2 km horizontal resolutions, see Fig. 1). In this region the nearshore dynamics consists of complex local river-tide-current interactions, but the mesoscale activity is also subject to an important interannual variability (Murray et al. 2001). Our quasi-equilibrium solutions for this configuration, forced either by SODA-POP or ROMS-Pacific at the boundaries, present a satisfactory seasonal cycle and level of mesoscale activity. Analysis of those solutions is currently underway.

With the objective of understanding the modulation of the mesoscale activity by local seasonal forcing (and remote basin-scale signals), we have continued our effort to significantly improve our US West Coast quasi-equilibrium solutions. During this time we developed a quite complete set of diagnostics to study the mesoscale processes. A special focus has been on the eddy contribution to the heat balance in coastal upwelling regions (for NAWC and SAWC in companion experiments at 5km horizontal resolution) and its possible upscaling effect. This analysis has been carried out for our quasi-equilibrium solutions (Capet et al. 2007b, Capet et al. 2007c) and should be undertaken in the interannual variability context.

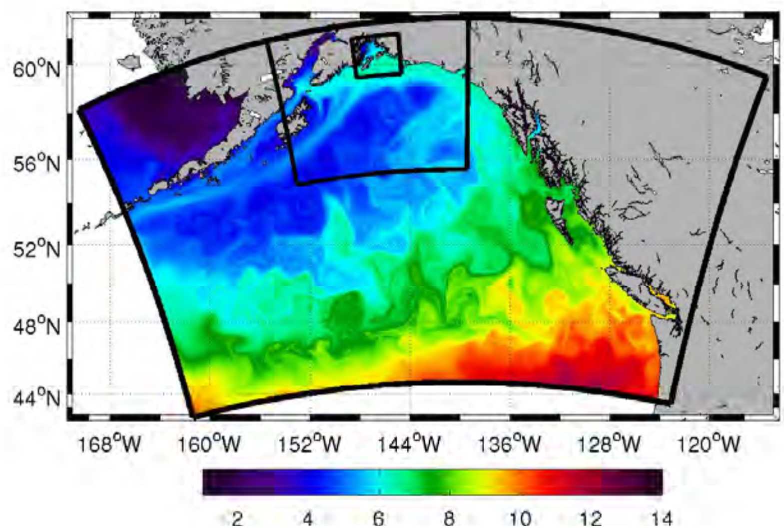

Figure 1. Gulf of Alaska ROMS embedded configuration

[Color graphs: Sea Surface Temperature [^{o} C] snapshot from ROMS Gulf of Alaska solution. Embedded grids are indicated by thick black lines, horizontal resolutions are 10 km, 3.3 km, and 1.2 km. For this solution the outer grid (10 km resolution) is forced at its open boundaries by the SODA-POP reanalysis.]

RESULTS

A careful analysis of the 1997-98 El Nino has been carried out for the SAWC solution (Colas et al. 2007) and the NAWC solution (Capet et al. 2007c). Emphasis was first put on the analysis of the SAWC region because its direct connection with the equatorial region makes it a perfect testbed for Pacific signal downscaling. A model/data comparison of SLA (using tide gauges and altimeter data) for both solutions has shown that the regional model correctly captures the ENSO signals. The phase and amplitude of poleward coastal waves associated with El Nino are in agreement with the observations. Off Peru the intensity of the upwelling appears to be determined by an interplay between alongshore poleward advection, related to coastal-trapped waves, and wind intensity but also determined by the cross-shore geostrophic flow and distribution of the water masses on a scale of 1000 km or more off Peru (Fig. 3). Our solution shows that the delay of upwelling recovery until fall 1998 is partly caused by the persisent advection of offshore stratified water of equatorial origin toward the coast.

Both in the NAWC and SAWC solutions, mesoscale activity appears to be modulated at interannual scales with conspicuous mesoscale eddy formation along the coast associated with El Niño pulses. Poleward currents (related to coastal wave propagation) are intensified during ENSO and their destabilization leads to anticyclonic eddies generation in the lee of major capes and headlands. An illustration is given in Fig. 2 with spiciness (i.e., linear combination of T and S orthogonal to density) maps for the same date of 3 consecutive years. The 1998 snapshot clearly shows a larger spiciness nearshore and large anticyclonic eddies filled with spicy water. Example of similar anticyclones formed during El Ñino off Peru are visible in Fig. 3. Although a more detailed quantitative analysis is required, these eddies evidently play a role in advecting anomalous water masses of equatorial origin.

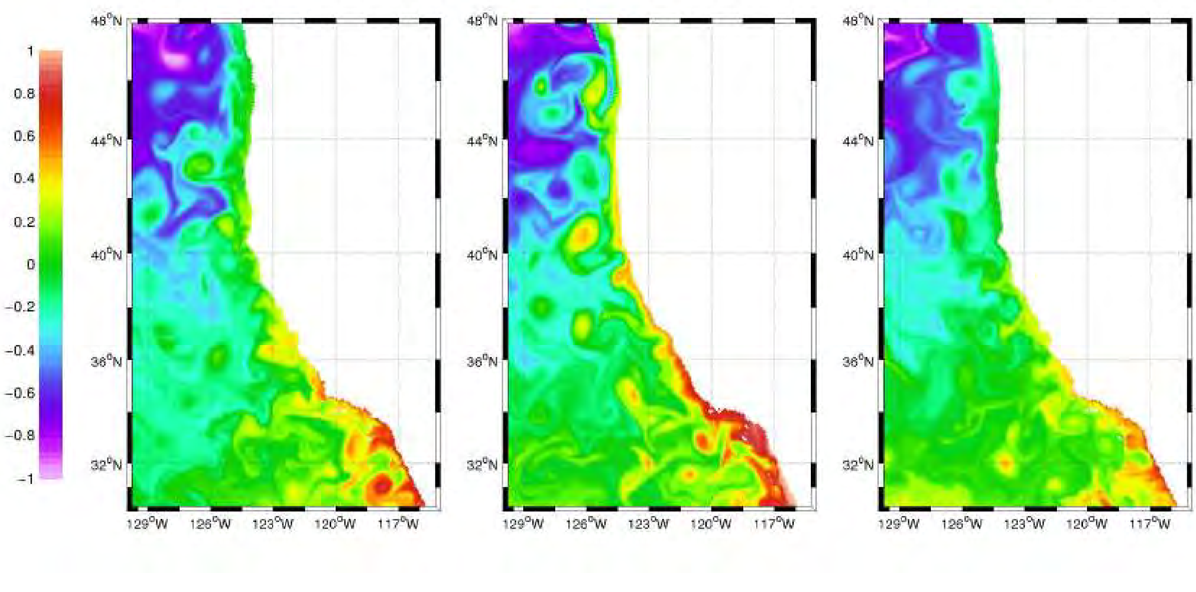

Figure 2. Snapshots of spiciness on the $\sigma_t = 25.8$ isosurface on February 15th of 1997 (left), 1998 (center) and 1999 (right), NAWC solution

[Color maps: Snapshots of spiciness on the $\sigma_t = 25.8$ isosurface on February 15th of 1997 (left), 1998 (center), and 1999 (right) for the regional NAWC ROMS solution (at 8 km horizontal resolution). Regional model open boundaries are forced by a CCSM-POP solution.]

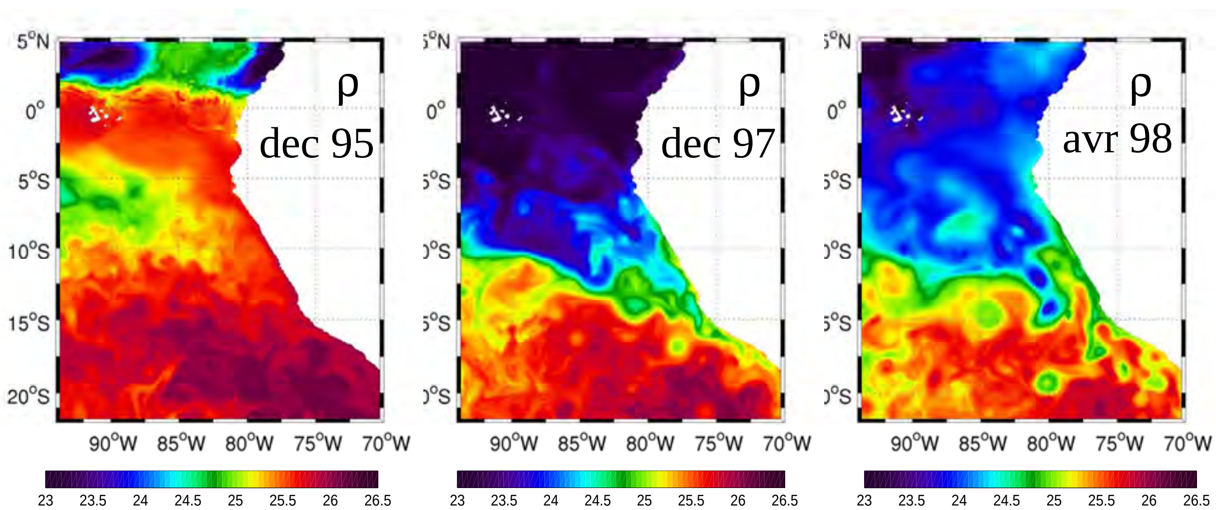

Figure 3. Horizontal potential density at 50 m in Dec 1995, Dec 1997, Apr 1998, SAWC solution

[Color maps: Horizontal potential density [kg.m^{-3}] at 50 m depth in Dec 1995, Dec 1997, Apr 1998 for the regional SAWC ROMS solution (at 8 km horizontal resolution). Regional model open boundaries are forced by a CCSM-POP solution.]

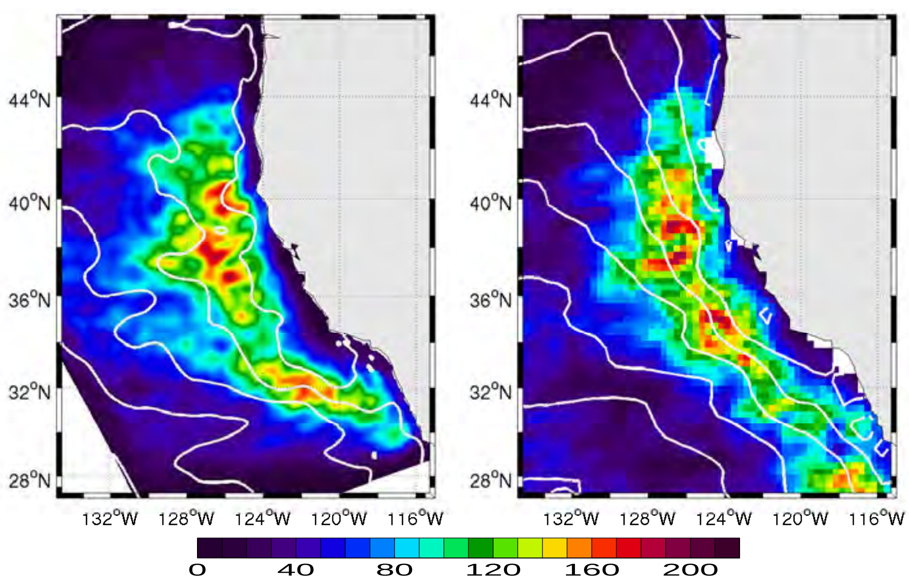

Figure 4. Eddy kinetic energy [cm^2.s^{-2}] - ROMS USWC and satellite observations

[Color maps: Eddy kinetic energy [cm^2.s^{-2}] for the model (left) and satellite observations (right). EKE for observations is computed from the improved DUACS SSH product for the period 2001-2006 (see www.jason.oceanobs.com/html/donne es/duacs/welcome uk.html).]

To better understand the role of the mesoscale eddies in eastern-boundary upwelling regions (also their modulation and their upscaling effect) we developed a detailed analysis of the heat balance in the NAWC and SAWC (Capet et al. 2007b, Capet et al. 2007c). For this study we developed a very similar configuration for USWC and SAWC at 5km resolution. Simultaneously we have significantly improved our USWC quasi-equilibrium solution (forced with a SODA climatology at the open boundaries and a

QSCAT wind climatology). The solution, compared with available observations, presents very satisfactory seasonnal cycle, mean circulation patterns and level of mesoscale activity. An illustration is given in Fig. 4, showing maps for model/observations eddy kinetic energy (EKE). Surface EKE comparison between a model and data is a stringent test of the upper-oceanic circulation. The model EKE has the same level as the EKE estimated from altimetry, and their spatial distribution are very similar (with a maximum offshore and minimum nearshore off Central California).

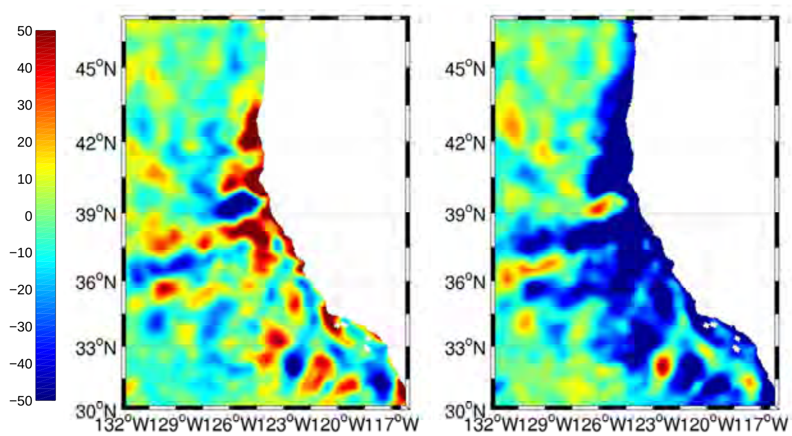

Figure 5. Vertically integrated (0-100 m depth) eddy (left) and mean (right) heat flux divergence for ROMS USWC solution.

[Color maps: Annual average of vertically integrated (0-100m depth) eddy (left) and mean (right) heat flux divergence [W.m^{-2}] for 9 years of ROMS USWC solution.]

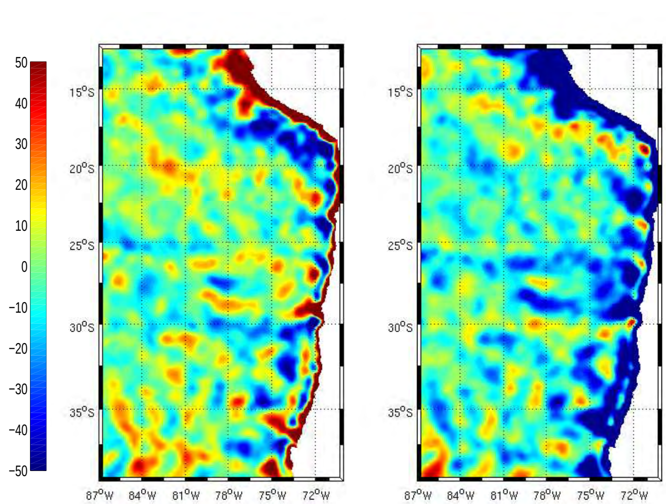

Figure 6. Vertically integrated (0-100 m depth) eddy (left) and mean (right) heat flux divergence for SAWC ROMS configurations.

[Color maps: Same as Fig. 5 for the Southern America configuration]

In Eastern-Boundary regions, where the mean circulation is generally weak, eddy fluxes can potentially influence the dynamical balances. Using these quasi-equilibrium solutions, we have examined the upper-oceanic heat balance because of its importance in the coupled atmosphere-ocean system. In those regions the heat balance is principally between the ocean-atmosphere heat flux and the advection terms (decomposed in mean and eddy contributions). Fig. 5 and 6 show those terms estimated for our NAWC and SAWC solutions (resp.). In the California region, nearshore, standing eddies play an important role shaping alternating strips of warming and cooling with magnitude over 50 W.m^{-2}. Nearshore the eddy term produces a warming to balance the cooling by mean advection/upwelling. Farther offshore, eddy flux modulates the heat budget with clear signs of cooling over extended regions having a temperature maximum located a few hundred kilometers offshore (Northern California-Oregon, Southern California Bight and off southern Peru). In these regions we find an eddy cooling equivalent to -30 W.m^{-2}, which indicates a locally significant effect of the eddy fluxes (hence an expected upscaling effect).

IMPACT/APPLICATIONS

This research will significantly contribute to the understanding of how large scale variability affects coastal properties that are difficult to measure (retention, dispersion and more generally properties intimately linked to oceanic turbulence) but are, nonetheless, essential oceanic variables (for operational, biogeochemical, as well as environmental reasons). Simulations including biogeochemistry are currently being computed for the 1990s decade, in collaboration with N. Gruber (ETH and UCLA).

TRANSITIONS & RELATED PROJECTS

This project is being done within a broader context both of coastal circulation modeling and forecasting using ROMS (*e.g.,* ONR's AOSN project in Monterey Bay, the Southern California (http://www.sccoos.org/), Central California (http://www.cencoos.org/), and Prince Williams Sound Coastal Oceanic Observing Systems (http://www.aoos.org). All these efforts will directly contribute to improved understanding of down-scaling mechanisms in the NAWC region. The Southern America part of this research is expected to be pursued in the framework of the VOCALS program (http://www.eol.ucar.edu/projects/vocals/).

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